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Optimum Degree of Bone-Implant Contact in Bone Remodelling Induced by Dental Implant

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Abstract

Dental implants are an effective, safe and predictable solution for patients suffering from tooth loss. An ideal level of bone-implant contact (osseointegration) is of direct impact on the success of an implant surgery. This leads to a question as whether higher degree of bone-implant contact would yield better surgical outcome. This study aims to determine an optimum degree of bone-implant contact using the newly developed bone remodelling algorithm through 2D finite element analysis. Four different degrees of bone-implant initial contact (25, 50, 75 and 100%) are considered and their influences on the resulting density distribution of jawbone are evaluated. Results indicate that, under 100N masticatory force, different initial bone-implant contacts lead to a similar and optimum degree of contact when an equilibrium state is reached. This result is consistent with clinical observations and findings. To account for normal to traumatic loading conditions, practical masticatory forces ranging from 100N to 400N are also considered, for initial contact of 50 and 75%, to evaluate the optimum degrees of bone-implant contact under different loading scenarios.

Keywords: Dental implant; bone remodelling; bone-implant contact percentage; optimization.

1. INTRODUCTION

A dental implant is a biocompatible titanium device that is surgically placed into the mandibular or maxillary bone to support a prosthetic tooth crown in order to replace missing teeth. Dental implants are an effective, safe and predictable solution for those who have lost a tooth or teeth due to dental caries, periodontal disease, injuries or other reasons. Despite high success rate of implantation when implants are

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correctly designed, manufactured and inserted in bone of good quality and quantity, failures do exist, especially in compromised sites and patients (Neukam and Flemmig 2006).

As a living tissue, bone is capable of optimizing its internal structure by redistributing its apparent density under external loads to fulfill its maximum function. This is known as the Wolff's law (1892). The process of bone redistributing its apparent density is termed as 'bone remodelling'. Since the early publication of Wolff, many theories describing bone remodelling process have been proposed. Frost (1964) suggested that internal and external remodelling should be distinguished, where internal remodelling refers to the alteration of density of bone tissue and external remodelling is the apposition and removal of bone tissue on the bone surface. Frost also suggested a trigger criterion for remodelling based on the strain magnitude. This concept was formally developed later by Cowin and Hegedus (1976) and Cowin and Nachlinger (1978) using the concept of adaptive elasticity under small strains, which was the first mathematically rigorous theory for adaptive growth and remodelling of bone. Carter (1984) proposed the concept of 'lazy zone', a threshold value, indicating that bone remodelling takes place only when the external stimuli exceed the 'lazy zone'. This concept was incorporated by Huiskes et al. (1987, 1992) who used the strain energy density as the stimulus signal to control bone remodelling. Mullender et al. (1994) and Mullender and Huiskes (1995) developed a physiological approach to simulate bone remodelling which assumed that osteocytes are sensitive to mechanical loading and are active in controlling the adaptation of bone mass in their environment.

Although many applications of bone remodelling theories are documented, majority of them focused on the prediction of density distribution in peri-implant bone tissues (Chou et al. 2008; Grupi et al. 2004; Li et al. 2007; Mellal et al. 2004). Little or no consideration was taken on the effect of bone-implant contact on bone remodelling outcomes. A full contact (100%) between the bone and implant is often assumed in existing biomechanical research. This is however inconsistent with clinical observations, which show that bone-implant contact is dependent on a variety of factors such as implant surface topography and bone quality. The present study aims to evaluate through 2D finite element analysis the optimum degrees of bone to implant contact under a range of masticatory forces.

2. METHODS

Lian et al. (2010) proposed a new bone remodelling algorithm which is a combination and further development of two existing and widely accepted bone remodelling theories. In this algorithm, the bone is assumed to have N sensor cells distributed uniformly over its volume (Mullender et al. 1994). An arbitrary sensor i measures a signal S_i , which is given as:

$$S_i = U_i / \rho_i \quad (1)$$

where U_i is the strain energy density and ρ_i is the density at the location of the sensor. The density $\rho(x,t)$ at the location x is regulated by the stimulus value $\Phi(x,t)$, to which all sensor cells contribute, relative to their distance from x . Hence,

$$\Phi_i(x,t) = \begin{cases} \sum_i^N f_i(x)(S_i^\alpha - (1+s)K) & \text{if } S_i > (1+s)K \\ 0 & \text{if } (1-s)K \leq S_i \leq (1+s)K \\ \sum_i^N f_i(x)(S_i^\alpha - (1-s)K) & \text{if } S_i < (1-s)K \end{cases} \quad (2)$$

where N is the total number of sensors; α is the order of non-linear remodelling equation; K is a reference signal of strain energy density per unit bone mass; s is in percentage denoting the ‘lazy zone’ region around the threshold value K . $f_i(\mathbf{x})$ is a spatial influence function in the following form:

$$f_i(\mathbf{x}) = e^{-[d_i(\mathbf{x})/D]} \quad (3)$$

where $d_i(\mathbf{x})$ is the distance between sensor i and location \mathbf{x} ; D is the rate of the spatial influence reduction.

The density $\rho(\mathbf{x}, t)$ is now governed by:

$$\frac{d\rho(\mathbf{x}, t)}{dt} = \tau\Phi(\mathbf{x}, t), \text{ with } 0 < \rho(x) \leq \rho_{max} \quad (4)$$

where ρ_{max} is the maximum density equivalent to that of a cortical bone, and τ is a time constant regulating the rate of the remodelling process. As the apparent density of bone tissue changes during the process of remodelling, Young’s modulus of bone changes accordingly. Carter and Hayes (1977) suggested a specific relationship between the elastic modulus (E) and density (ρ), i.e:

$$E(x, t) = 3790 \times \rho^3 \quad (5)$$

The applicability of the proposed algorithm on density distribution of bone has been verified using Mullender et al’s 2D plate model as well as a 2D bone-implant model (Lian et al. 2010).

3. FINITE ELEMENT ANALYSIS SIMULATION

To evaluate the effect of different bone-implant contact on the density distribution of jawbone and the optimum degree of such contact under different loading scenarios, a 2D slice at the position of first premolar is taken from the entire mandibular bone. The system of crown, abutment, abutment screw, implant and bone are modeled using 2D plane strain elements. The cortical and cancellous bones are identified based on CT scan images. The implant dimensions are based on those of Neoss (2006). Fig. 1(a) shows an implant of diameter 4.5mm and length 11mm, and a mandible section with a cortical bone thickness of 1 mm. The implant is conical with 2° taper and has a helical thread. A small area of bone surrounding the implant (0.2mm from tip of implant thread) is designated as connective tissue, constituting a mix of hard and soft tissue to simulate varying degrees of bone to implant contact (see Fig. 1(a)). Based on the work of Chou et al. (2008), the implant system is loaded with an occlusal load of 100N on the crown at an angle of 11° and a uniformly distributed pressure of 500kPa on the outer surface of the cortical bone with the latter representing forces due to jaw flexure. In the present study, typical values of Young’s modulus (E) of bone, implant components as well as crown are selected based on the work of Menicucci et al. (2002). The Poisson’s ratio for all components is taken as 0.3. The load and boundary conditions, and the material properties are detailed in Fig. 1(b).

When an implant is surgically placed into jawbone, the bone-implant interface can be divided into regions with and without direct contact (Simmons et al. 2001). To simulate different degrees of bone-implant contact, a certain percentage of connective tissue elements is randomly selected and assigned the properties of bony tissue. The remaining elements within the connective tissue are assigned the properties of soft tissue. According to Lu et al. (2005) and Xing et al. (2002), Young’s moduli of the bony and soft tissues are taken as 2.4GPa and 70MPa, respectively. In this study, four bone-implant contacts (i.e. 25, 50, 75 and 100%) are considered to evaluate their effect on the density distribution of jawbone. Note that 25% contact represents 25% bony tissue and 75% soft tissue.

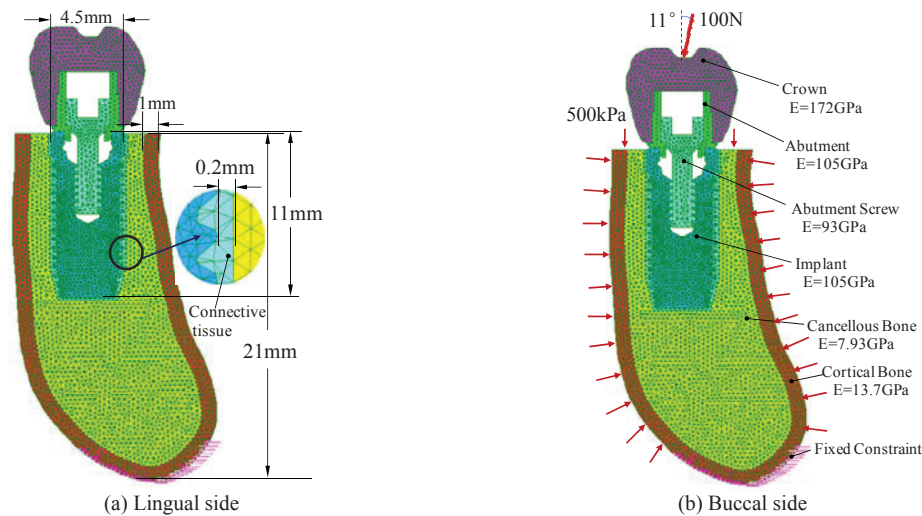


Figure 1: Finite element model of implant and jawbone: (a) Dimensions; (b) Load, boundary conditions and material properties.

Cancellous bone is often more metabolically active and responsive to stimuli than cortical bone (Jacobs 2000). Therefore in the remodelling process, density distribution of cortical bone is assumed to be unchanged. However the ratio of bony-soft tissue does not remain constant during the process. Hence the connective tissue is also remodelled together with cancellous bone to represent a clinical reality. The cancellous bone has a uniform initial density distribution of $\rho=1.279 \text{ g/cm}^3$ and the corresponding Young's modulus is 7.93GPa (Eq. (5)). It is worthwhile noting that there are no standard rules in the determination of bone remodelling parameters as specified in Eqs. (2) and (4). Such parameters as K , the reference signal of SED, s , the 'lazy zone' effect and τ , the time constant regulating the remodelling rate are found to be quite different in the literature (see Table 1).

Table 1: Bone remodelling parameters used in published literature

	K	s	τ or $\tau \Delta t$
Chou et al. (2008)	25 Nm/kg	65%	$0.005 \text{ kg}^4/\text{Nm}^4 (\tau \Delta t)$
Li et al. (2007)	0.004 J/g (4 Nm/kg)	—	$1.0 (\text{g/cm}^3)^2 (\tau)$
Mellar et al. (2004)	0.004 J/g (4 Nm/kg)	10%	$1.0 (\text{g/cm}^3)^2 (\tau)$

In order to compare the effect of four different bone-implant contacts, the following bone remodelling parameters are kept constant for all scenarios. According to Chou et al. (2008), the maximum and minimum densities are assumed to be $\rho_{\max}=1.5347 \text{ g/cm}^3$ and $\rho_{\min}=0.064 \text{ g/cm}^3$ respectively which corresponds to Young's moduli of 13.7GPa and 1kPa respectively; the sensor cell distribution is assumed to be uniform and is located at the centre of each element; the influence reduction parameter is taken as $D=0.2 \text{ mm}$. Using Table 1 as a guideline, other parameters are chosen as: $s=20\%$, $\tau=1 (\text{g/cm}^3)^2/(\text{MPa time-unit})$ and $K=16 \text{ Nm/kg}$.

It should be noted that masticatory force is not a constant value. To account for normal to traumatic loading conditions, practical masticatory forces ranging from 100N to 400N are also considered, for initial contact of 50 and 75%, to evaluate the optimum degrees of bone-implant contact under different loading scenarios. Note also that the angle of the masticatory forces remain unchanged.

4. RESULTS AND DISCUSSION

Presented in Fig. 2 are the predicted results of density distributions in cancellous bone and connective tissue for four different bone-implant contact scenarios under 100N masticatory force. As can be seen the final density distributions are almost identical for this four cases. The only noticeable difference is the area located on the buccal side of the implant where the bone tissue demonstrates an average density. This is particularly true for 50%-100% bone-implant contact scenarios. For the 25% contact, this area is a mix between bone resorption and formation.

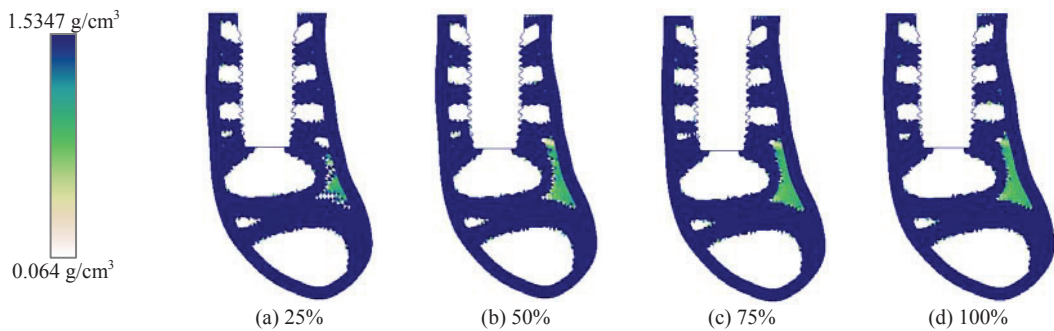


Figure 2: Density distribution under different initial bone-implant contact.

Fig. 3 presents a comparison of the predicted density distribution results (for 75% contact) with published numerical prediction (Chou et al. 2008) and clinical observations on a baboon's jawbone surrounding a dental implant (Watzak et al. 2005). The overall density distributions in the three figures are quite similar in the following aspects: (1) trabecular-like pattern surrounding the implant as highlighted by region A; (2) lower density area (bone resorption) below the implant as highlighted by region B. It should be noted that Chou et al.'s algorithm is based on Huiskes et al.'s (1992) theory with a consideration of high-order effect. However, the 'lazy-zone' effect was ignored. In addition, with a focus on the influence of different types of implant systems on the density distribution, their studies did not cover varying bone-implant contact percentages.

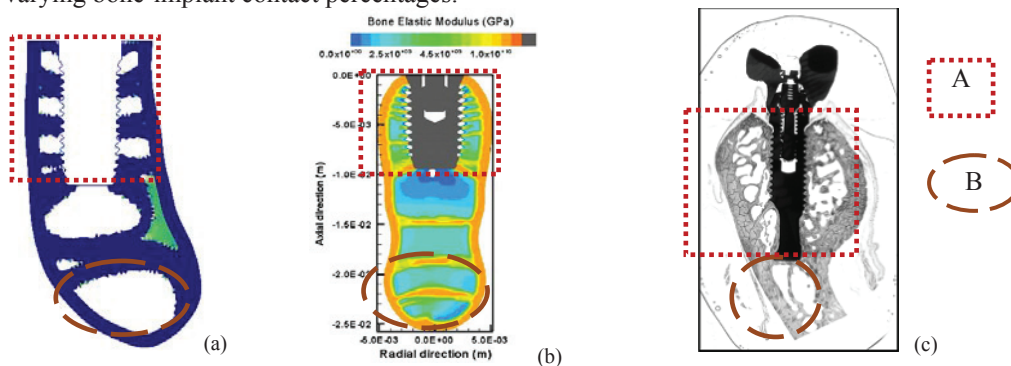


Figure 3: Bone remodeling comparison: (a) Predicted result (75% contact); (b) Chou et al.'s (2008) prediction; (c) Watzak et al.'s (2005) clinical observation.

Shown in Fig. 4 is the relationship between bone-implant contact percentage and bone mass after remodelling is complete. As indicated, the bone mass reaches its maximum value for 100% contact and a similar bone mass is achieved for 50% and 75% contact. Furthermore, the difference between the maximum (100% contact) and minimum (25% contact) bone mass is less than 0.5%. This suggests that the assumed initial contact percentage has little influence on the bone mass upon completion of bone remodelling. Fig. 5 further compares the bone-implant contact percentage before and after bone remodelling. Again initially assumed different contact percentages result in a rather constant (about 58%) percentage of contact after bone remodelling. Figs. 2, 4 and 5 all demonstrate that the initial bone-implant percentages have little impact on the final density distribution and bone mass. Upon reaching a balanced bone resorption and formation throughout bone remodelling process, the bone-implant contact remains almost constant at about 58%. Testori et al. (2002) found a bone-implant contact of 64.2% for an immediately loaded implant. Through a histology study, Degide et al. (2003) also discovered about 65% to 70% contact for two immediately loaded implants. This further verifies that the findings of the present study are in a good agreement with those of the published literature.

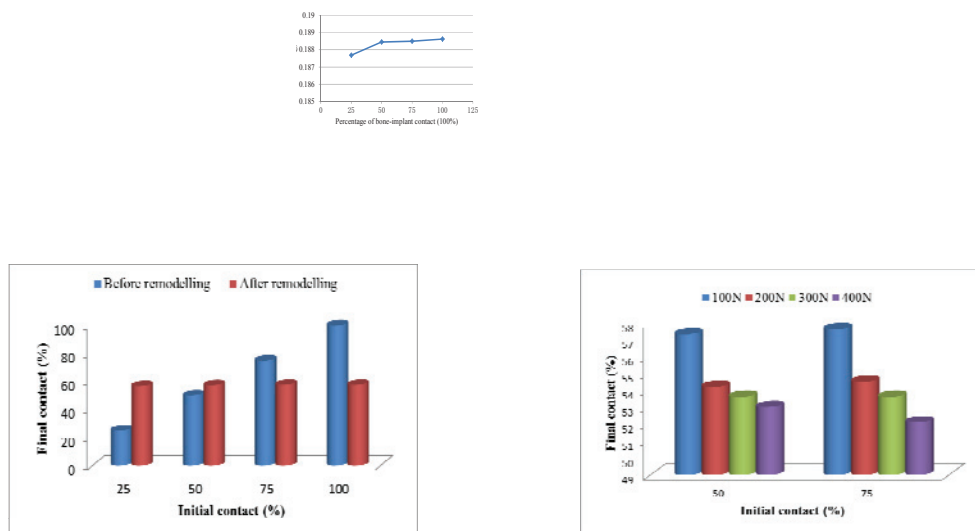


Figure 4: Bone mass versus contact percentage after remodeling; Figure 5: Bone-implant contact percentage before and after bone remodeling; Figure 6: Bone-implant contact percentage under different masticatory forces

Based on the above finding, it becomes interesting to examine the impact of different masticatory forces on bone density distribution based on two selected bone-implant contact percentages (i.e. 50% and 75%). As illustrated in Fig. 6, increased masticatory forces (from 100N to 400N) result in a slight decrease in the final but again stable bone-implant contact percentage (from about 58% to about 52-53%). Fig. 7 also demonstrates that the final bone density distribution changes accordingly when the masticatory force increases. Not only more bone resorption takes place around the implant, but also more bone formation on the buccal side under the implant. The increased bone formation is highlighted by the decreased area of region A (shown in Fig. 7(a)), which implies that more bone is formed in order to resist the increasing masticatory force. This outcome is true for all three different bone-implant contacts. Further, despite the changes in the overall density distribution patterns for different contacts and different forces, the total areas of bone resorption and formation seem to balance each other out, thereby resulting in little or no change in the total mass of bone tissue.

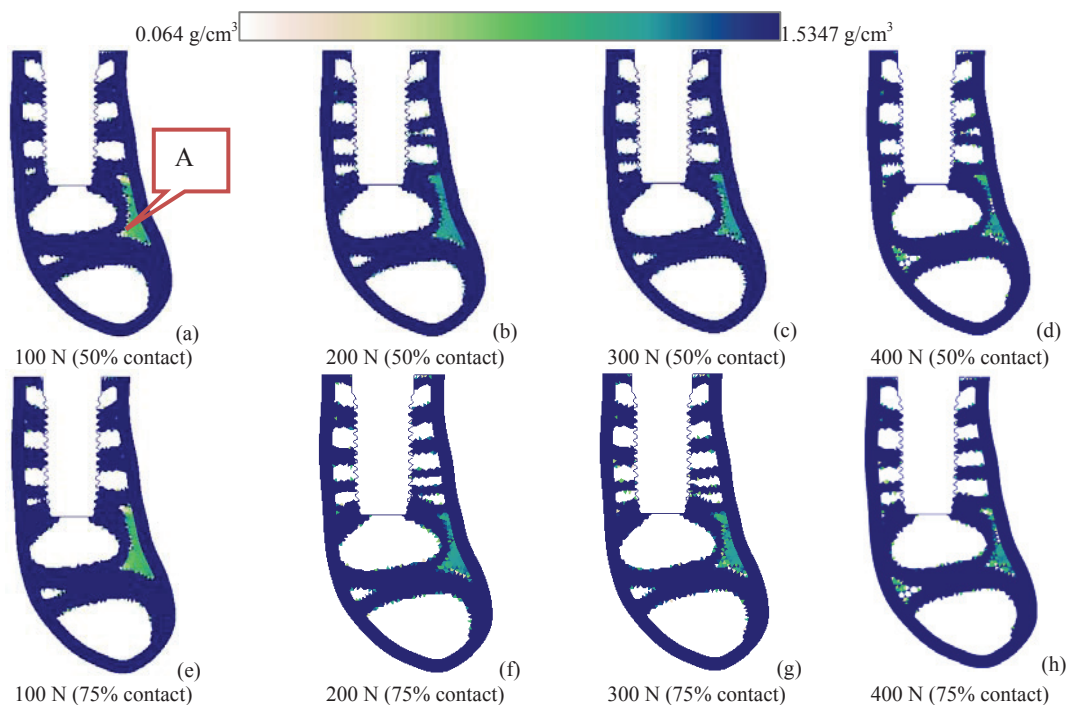


Figure 7: Density distribution under different bone-implant contacts and masticatory forces.

5. CONCLUSION

Using a newly proposed remodelling algorithm, this study evaluates the influence of different degrees of bone-implant contact and different levels of masticatory forces on bone remodelling induced by dental implant. The present 2D finite element study demonstrates that the initial contact percentage (25-100%) has little influence on the ultimate density distribution in the bone. Increased masticatory forces influence the overall pattern of density distribution in terms of areas of bone resorption and formation. However the total mass of bone tissue does not change significantly. Further, increased masticatory forces result in a slight decrease in the final but again stable bone-implant contact percentage when an equilibrium state is reached by bone remodeling. The results are consistent with the clinical observations and findings.

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